

Udo W. Pohl

Epitaxy of Semiconductors

Introduction to Physical Principles

 Springer

Contents

- 1 Introduction 1**
 - 1.1 Epitaxy 1
 - 1.1.1 Roots of Epitaxy 1
 - 1.1.2 Epitaxy and Bulk-Crystal Growth 4
 - 1.2 Issues of Epitaxy 4
 - 1.2.1 Convention on Use of the Term “Atom” 4
 - 1.2.2 Assembly of Atoms 5
 - 1.2.3 Tasks for Epitaxial Growth 6
 - References 9
- 2 Structural Properties of Heterostructures 11**
 - 2.1 Basic Crystal Structures 11
 - 2.1.1 Notation of Planes and Directions 11
 - 2.1.2 Wafer Orientation 13
 - 2.1.3 Face-Centered Cubic and Hexagonal Close-Packed Structures 13
 - 2.1.4 Zincblende and Diamond Structures 14
 - 2.1.5 Rocksalt and Cesium-Chloride Structures 16
 - 2.1.6 Wurtzite Structure 16
 - 2.1.7 Thermal Expansion 17
 - 2.1.8 Structural Stability Map 19
 - 2.1.9 Polytypism 20
 - 2.1.10 Random Alloys and Vegard’s Rule 21
 - 2.1.11 Virtual-Crystal Approximation 26
 - 2.2 Elastic Properties of Heterostructures 26
 - 2.2.1 Strain in One and Two Dimensions 26
 - 2.2.2 Three-Dimensional Strain 27
 - 2.2.3 Hooke’s Law 29
 - 2.2.4 Poisson’s Ratio 31
 - 2.2.5 Pseudomorphic Heterostructures 32
 - 2.2.6 Critical Layer Thickness 35

2.2.7	Approaches to Extend the Critical Thickness	39
2.2.8	Partially Relaxed Layers and Thermal Mismatch	42
2.3	Dislocations	44
2.3.1	Edge and Screw Dislocations	45
2.3.2	Dislocation Network	46
2.3.3	Dislocations in the fcc Structure	47
2.3.4	Dislocations in the Diamond and Zincblende Structures	49
2.3.5	Dislocation Energy	51
2.3.6	Dislocations in the hcp and Wurtzite Structures	54
2.3.7	Mosaic Crystal	57
2.4	Structural Characterization Using X-Ray Diffraction	58
2.4.1	Bragg's Law	58
2.4.2	The Structure Factor	59
2.4.3	The Reciprocal Lattice	61
2.4.4	The Ewald Construction	63
2.4.5	High-Resolution Scans in the Reciprocal Space	64
2.4.6	Reciprocal-Space Map	67
2.5	Problems Chap. 2	70
2.6	General Reading Chap. 2	73
	References	74
3	Electronic Properties of Heterostructures	79
3.1	Bulk Properties	79
3.1.1	Electronic Bands of Zincblende and Wurtzite Crystals	79
3.1.2	Strain Effects	81
3.1.3	Temperature Dependence of the Bandgap	87
3.1.4	Bandgap of Alloys	88
3.2	Band Offsets	90
3.2.1	Electron-Affinity Rule	91
3.2.2	Common-Anion Rule	92
3.2.3	Model of Deep Impurity Levels	93
3.2.4	Interface-Dipole Theory	95
3.2.5	Model-Solid Theory	96
3.2.6	Offsets of Some Isovalent Heterostructures	97
3.2.7	Band Offset of Heterovalent Interfaces	97
3.2.8	Band Offsets of Alloys	101
3.3	Electronic States in Low-Dimensional Structures	101
3.3.1	Dimensionality of the Electronic Density-of-States	102
3.3.2	Characteristic Scale for Size Quantization	106
3.3.3	Quantum Wells	107
3.3.4	Quantum Wires	112
3.3.5	Quantum Dots	116
3.4	Problems Chap. 3	123
3.5	General Reading Chap. 3	125
	References	125

4	Thermodynamics of Epitaxial Layer-Growth	131
4.1	Phase Equilibria	131
4.1.1	Thermodynamic Equilibrium	132
4.1.2	Gibbs Phase Rule	134
4.1.3	Gibbs Energy of a Single-Component System	135
4.1.4	Phases Boundaries in a Single-Component System	139
4.1.5	Driving Force for Crystallization	140
4.1.6	Two-Component System	143
4.2	Crystalline Growth	148
4.2.1	Homogeneous Three-Dimensional Nucleation	148
4.2.2	Heterogeneous Three-Dimensional Nucleation	152
4.2.3	Growth Modes	154
4.2.4	Equilibrium Surfaces	155
4.2.5	Two-Dimensional Nucleation	161
4.2.6	Island Growth and Coalescence	164
4.2.7	Growth without Nucleation	166
4.2.8	Ripening Process After Growth Interruption	168
4.3	Problems Chap. 4	168
4.4	General Reading Chap. 4	169
	References	169
5	Atomistic Aspects of Epitaxial Layer-Growth	171
5.1	Surface Structure	171
5.1.1	The Kink Site of a Kossel Crystal	172
5.1.2	Surfaces of a Kossel Crystal	173
5.1.3	Relaxation and Reconstruction	175
5.1.4	Electron-Counting Model	176
5.1.5	Denotation of Surface Reconstructions	179
5.1.6	Reconstructions of the GaAs(001) Surface	181
5.1.7	The Silicon (111)(7 × 7) Reconstruction	184
5.2	Kinetic Process Steps in Layer Growth	186
5.2.1	Kinetics in the Terrace-Step-Kink Model	186
5.2.2	Atomistic Processes in Nucleation and Growth	188
5.2.3	Adatoms on a Terraced Surface	192
5.2.4	Growth by Step Advance	194
5.2.5	The Ehrlich-Schwoebel Barrier	197
5.2.6	Effect of the Ehrlich-Schwoebel Barrier on Surface Steps	199
5.2.7	Roughening of Surface Steps	201
5.2.8	Growth of a Si(111)(7 × 7) Surface	204
5.2.9	Growth of a GaAs(001) β ₂ (2 × 4) Surface	207
5.3	Self-organized Nanostructures	209
5.3.1	Stranski-Krastanow Island Growth	209
5.3.2	Thermodynamics Versus Kinetics in Island Formation	215
5.3.3	Wire Growth on Non-planar Surfaces	217

5.4	Problems Chap. 5	220
5.5	General Reading Chap. 5	221
	References	221
6	Doping, Diffusion, and Contacts	225
6.1	Doping of Semiconductors	225
6.1.1	Thermal Equilibrium Carrier-Densities	226
6.1.2	Solubility of Dopants	231
6.1.3	Amphoteric Dopants	235
6.1.4	Compensation by Native Defects	236
6.1.5	DX Centers	239
6.1.6	Fermi-Level Stabilization Model	241
6.1.7	Delta Doping	243
6.2	Diffusion	247
6.2.1	Diffusion Equations	247
6.2.2	Diffusion Mechanisms	250
6.2.3	Effective Diffusion Coefficients	252
6.2.4	Disordering of Heterointerfaces	255
6.3	Metal-Semiconductor Contact	259
6.3.1	Ideal Schottky Contact	259
6.3.2	Real Metal-Semiconductor Contact	263
6.3.3	Practical Ohmic Metal-Semiconductor Contact	265
6.3.4	Epitaxial Contact Structures	267
6.4	Problems Chap. 6	270
6.5	General Reading Chap. 6	271
	References	271
7	Methods of Epitaxy	275
7.1	Liquid-Phase Epitaxy	276
7.1.1	Growth Systems	277
7.1.2	Congruent Melting	279
7.1.3	LPE Principle	281
7.1.4	LPE Processes	283
7.2	Metalorganic Vapor-Phase Epitaxy	286
7.2.1	Metalorganic Precursors	287
7.2.2	The Growth Process	290
7.2.3	Mass Transport	293
7.3	Molecular Beam Epitaxy	299
7.3.1	MBE System and Vacuum Requirements	300
7.3.2	Beam Sources	302
7.3.3	Uniformity of Deposition	307
7.3.4	Adsorption of Impinging Particles	309
7.4	Problems Chap. 7	310
7.5	General Reading Chap. 7	311
	References	311

Appendix Answers to Problems 315

Index 319

Fundamental Physical Constants 325